DESIGN OF EXOSKELETON FOR MUSCULOSKELETAL SUPPORT OF HUMAN BODY UNDER LOW GRAVITY CONDITIONS AND ITS PERFORMANCE EVALUATION BY FLUID DYNAMIC ANALYSIS

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ABSTRACT

The human body has evolved and adapted to the environmental conditions it lives in. Any drastic changes in these conditions may affect its normal functioning. This makes space travel a potential hazard to the astronauts due to its harsh environment. To achieve a safe travel in either long commute to a planet or a short trip to ISS and the moon, the environmental conditions have to be controlled. The cabin of spacecraft and the spacesuit are designed to control the temperature and pressure according to the requirements of the astronauts. But problems arise due to the prevailing low-gravity and microgravity conditions in space.

Compared to other issues, the loss of bone mineral density, hydrostatic pressure reduction, and orthostatic hypotension are badly affecting the astronauts from the past. Although there are some curative adoptions, many of them are not quite effective. This paper summarizes the use of a specially designed exoskeleton for the human body which can be used in space travel to lower some of the health risks which arise due to change in gravity.

The exoskeleton was designed considering different joints and their Range of Motions (ROM) to support normal functional movements of the body in space. It covers from shoulders to foot which contains fluid-carrying tubes embedded into it. These fluid lines and different bio-mimicked joints form as functional elements in the exoskeleton. Fluid dynamic analysis is used to evaluate the nature of fluid flow and to check its biomechanical performance. The results obtained are used to investigate its biological and medical relevance in the areas of musculoskeletal and cardiovascular systems. In view of the complexity in the fabrication of embedded fluid lines, this design was made compatible with additive manufacturing for ease of fabrication.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

ρ Density, kg/m^3

f Friction factor (dimensionless)

v Specific volume, m^3/kg

$\triangle$ Delta (change or difference between higher and lower values)

A Cross-sectional area, m^2

D Diameter, m

F Force, N

g Acceleration due to gravity, m/s^2

P Pressure, N/m^2

$\dot{m}$ Mass flow rate, kg/s

Q Discharge, m^3/s

V Velocity, m/s

K loss coefficients for bends and fittings, (dimensionless)

L Length, m

C_f Fluid capacitance, m^5/N

C_d co-efficient of discharge (dimensionless)

Subscripts

Cap – Cap side

Rod – Rod side

Abbreviations

ROM Range of Motion

AM Additive manufacturing

MSIS Man-Systems Integration Standards

INTRODUCTION

Space travel is fascinating to many people. Every human at least once in their lifetime dreams to be an astronaut or to experience the free float in space but it has a hostile climate that possess a severe threat to human life. This makes it riskier for allowing human space travel, unlike other unmanned space expeditions[1].

The human body is a complex system. Although it can adjust to some changes like some climatic changes and change when one moves to a different country, it is nearly inflexible to drastic changes. During evolution, the human body was made to adjust and work under some specific conditions. Any change in those values of normal conditions can cause mild to severe effects on its functioning which can directly affect its health[2]. But there is a need for human space travel.

Despite of many potential threats space possess like lack of required oxygen levels, change in gravity, Sun's UV radiation, space bacteria, small floating meteorites, etc., which makes it impossible to move as we move on the earth still human challenge for space travel. Oxygen requirement is the major problem which made to design a special suit known as spacesuit for astronauts who are being sent to ISS for carrying out some work over there. This suit ensures safety from those hazards mentioned above but that doesn't stand as a solution for all as astronauts are experiencing many health issues during and after space travel. Over these years with some investigations and data collected from the post-flight experience of astronauts, it can be seen that almost all the human body systems are being affected with space travel[3].

Some of the physiological changes resulted from long-duration space travel majorly affecting the human body are Loss of bone mineral density, loss of skeletal muscle orthostatic hypotension, loss of hydrostatic pressure, change in pulmonary circulation and gas exchange, ileus, malabsorption, ataxia, motion sickness, disturbance in fine & gross motor function, altered sleep, the effect of radiation on gametes, renal calculi, anemia, and potential immunological depression[4].

There is a need to address these issues and get a remedy to suppress or reduce these effects on the human body because technologically we are sound enough to send humans to other planets in search-of life and colonization[5]. These projects for colonization will cause a non-linear change to the adaptability abilities of the human body, at any period between travel to exoplanet and earth i.e., travel from earth to some planet, some period of stay on other planets, traveling back to earth and post-flight period on earth. During all those stages humans will experience different gravity. We don't have specific data related to how it is going to affect our body and unlike other engineered structures or bodies, one cannot draw conclusions on how well our body can sustain those changes using our remedies made in anticipation. Comparatively, of all the issues mentioned above, those related to musculoskeletal and cardiovascular systems have been affecting astronauts even with a short flight to ISS.

Issues related to musculoskeletal and cardiovascular systems

1. **Loss of bone mineral density and muscle atrophy (musculoskeletal system):**
   In the human body, bones continuously change their shape & size, unlike other tissues, bone tissues are remodeled by depositing and removing bone cells; deposition by osteoblasts & selective absorption by osteoclasts. This process is continuous, under the earth's gravity with the help of body weight, bones undergo compression to repeat a cycle that maintains healthy bone density. So, in the absence of gravity, this cyclic process gets interrupted which leads to loss of bone density[6]. Also, due to no proper exercise in low gravity conditions (which can be even obtained with daily activities on earth), muscle degeneration starts to take place leading to muscle atrophy.

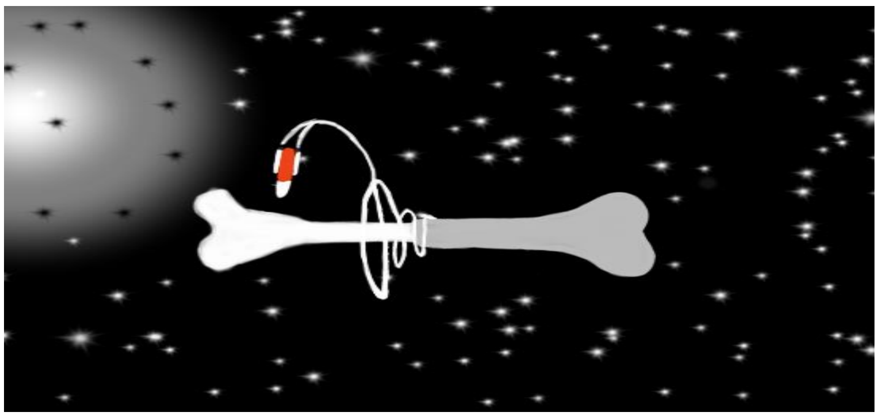


Figure 1. Illustration showing bone density loss with space travel.

2. **Orthostatic hypotension and reduced hydrostatic pressure (cardiovascular system):**
   Orthostatic hypotension is the sudden fall in the blood pressure resulting from a long duration of the motionless condition. This along with the reduced hydrostatic pressure resulted from the loss of contact with the ground for foot, changes the blood circulation pattern[7] by pumping less blood to the caudal region (lower) as shown in Figure 2. This moves a large volume of blood to the cranial region (head) making the face fluffier (puffed face) and volume of legs are narrowed (chicken legs).

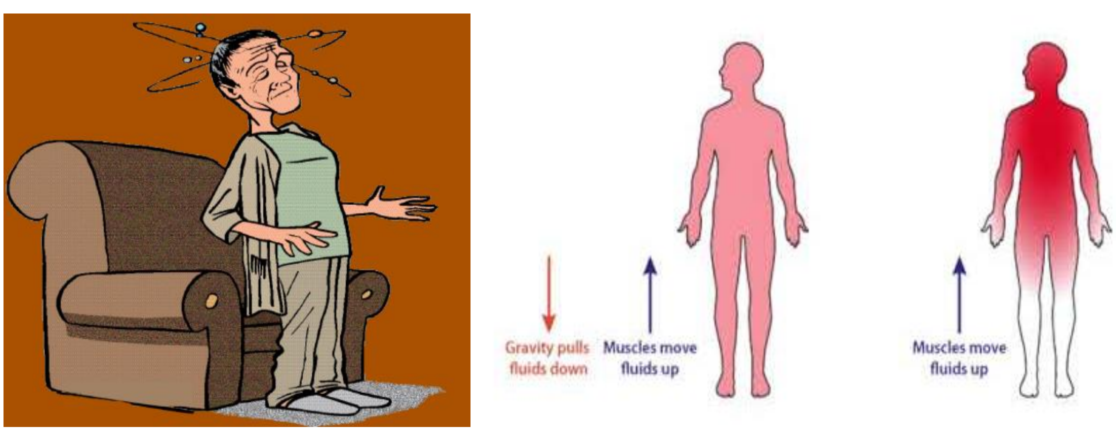


Figure 2. Orthostatic hypotension and change in blood flow pattern

Existing remedies and their issues

- **Musculoskeletal problem remedies:**
  To compensate for the loss of bone mineral density and degeneration of skeletal muscle or muscle atrophy, two methods are being adopted:
  1) A special diet is given to them, pre-flight immense exercising[8] to get them adapted with the space exercising which gives rise and falling curves during exercise. Also, some medications are given to them to ensure there is a reduced amount of loss in bone density which releases hormones targeting the remodelling of bone tissue or cells as discussed in the previous section. 2) Considering the person with higher bone density for a mission.

- **Issues:**
  There is a potential risk of exercise-induced muscle damage[9] due to unaccustomed and over-exercise which is a serious issue. This can lead to cause permanent muscle tissue damage[10]. It is unlikely to find a person with higher bone density all the time. Also, it may be unfair to make it as a factor to decide a person for space travel. Using medicine always has undesirable side effects.

- **Cardiovascular problem remedies**
  To reduce orthostatic hypertension and loss of hydrostatic pressure, astronauts are given pharmacological interveners. Those medicines are targeted to intervene with a specific organ or a part of the body to bring them into normal functioning during some adverse conditions. Creating artificial gravity is also under consideration as a solution to these problems.

- **Issues:**
  Using Medicine like neuro-interveners hinders the brain's normal activity which alters its functioning and always produces inevitable side effects. The creation of artificial gravity is not possible soon.

Because of these issues, it is necessary to look for alternative solutions which can solve the above-discussed problems. Also, that solution has to overcome the mentioned issues. The solution can be any device of two types that work from inside of the body like drugs or other instruments like pacemakers and external aiding devices like a spacesuit.

It is always desirable to use external aiding devices because there will be many issues when integrating foreign objects into the human body, also it has to clear many ethical & clinical guideline processes that are mandatory for approval of the device for use.

This made us choose an externally working exoskeleton for supporting our human body in low gravity conditions. Our exoskeleton will wrap around the body covering from shoulders to foot, majorly controlling actions or movements of the human body (especially limbs) to reduce the effect of low gravity effect on our body systems (musculoskeletal and cardiovascular system).

BIOLOGICAL CONSIDERATIONS

It is important to discuss biological considerations before starting the actual product design. In the usual process only the local need and its effect of design on human body is considered. Unlike engineering objects human body is a very complex system in which local effect may have a greater impact on all systems of body. So, it is very important to take as many considerations as we can to ensure a safer design that can work without inducing any possible challenges to the person who is using it. Let us start by looking at the joints in Figure 3. The synovial joints are the major type of body joints that allow for the bones to either slide, rotate or twist around it (sometimes they do all of these). These forms as the major part, which allows the human body for complex movements with the pick, grasp, moving and gait positions.

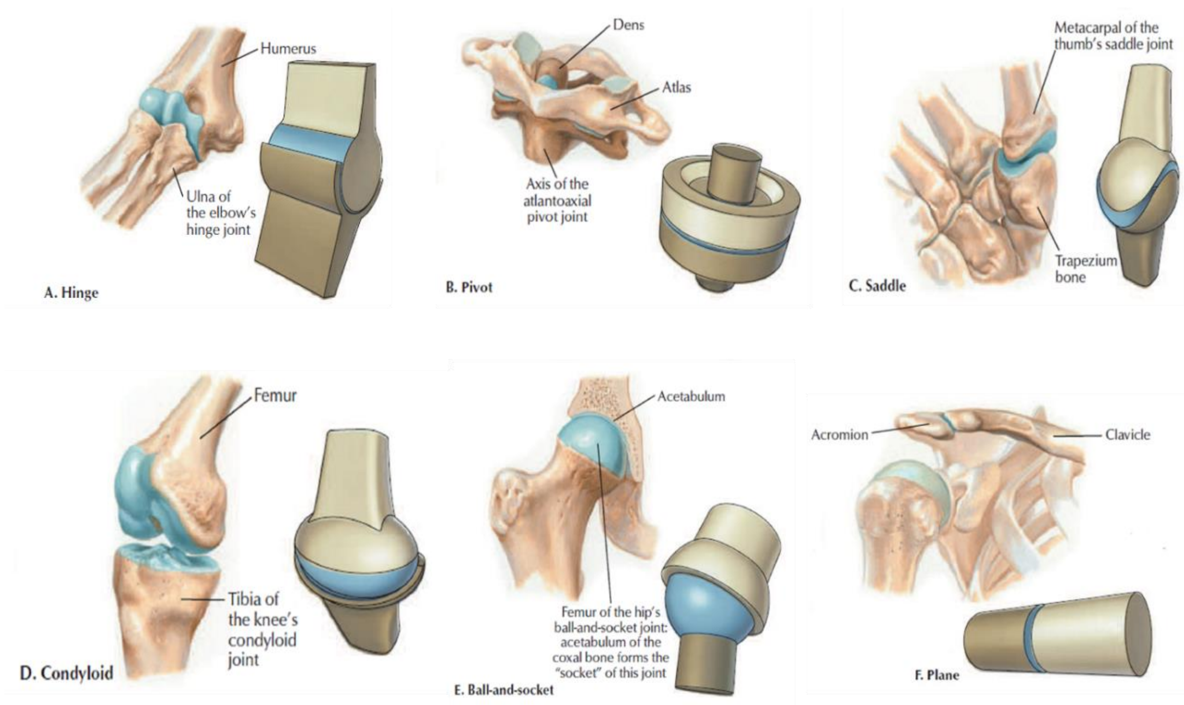


Figure 3. Some Synovial joints of human body demonstrating the joint movements[11]

Skeletal muscles attached to the human skeleton, work together to put the body in motion, which indeed helps the human body to be in a stable posture during static and dynamic movements (to be precise our body will almost never be in a static posture). Now, imagine our body as a series of links or segments as shown in figure 4, joined together using different types of joints discussed before. These links will be moving or rotating around the axis of rotation of that joint. How far or the range to which each link is allowed to move or rotate around that joint is given by "Range of motion (ROM)". ROM is the extent of movement of a joint, measured in degrees of a circle. It is the Joint movement (either active, passive, or a combination of both) carried out to assess, preserve, or increase the arc of joint motion. This ROM is controlled by skeletal muscle to prevent the crossover of bones (than the required range or allowable range) and prevents form internal damage to bones, joints and tissues around them.

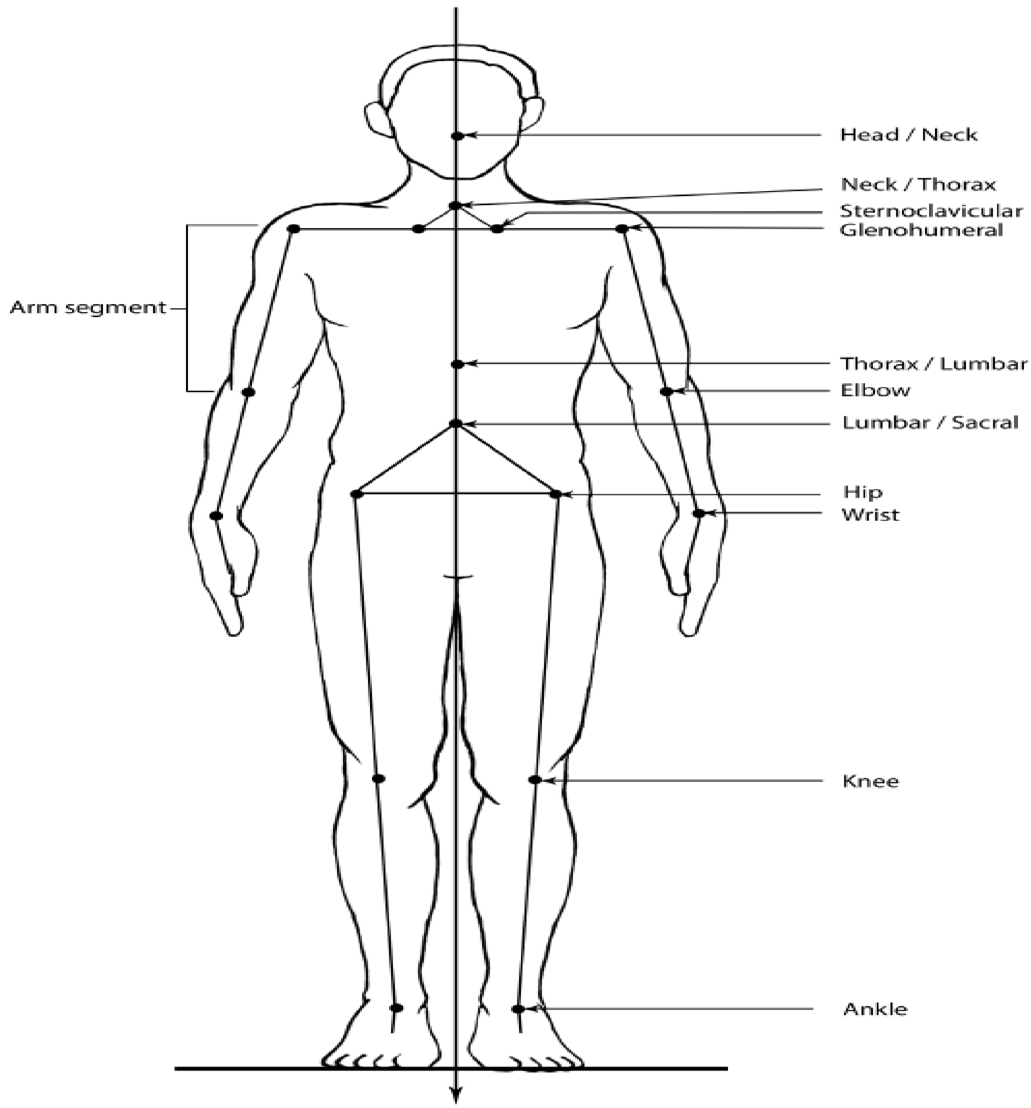


Figure 4. Human body linkages[12]

Human skeletal muscles always work in tandem with other muscles, this is to restrict or control the moment or ROM of different parts of body (surprisingly, this is what lead us to the term Range of Motion). For example, consider biceps and triceps of human body, during any operation one elongates while the other muscle contracts to control the humerus movement with the forearm (radius & ulna). These all contribute to body motions as shown in figure 5, which stands as an important biological consideration.

Any product designed should not interfere with these movements which can be harmful for the bone health, so the product design should accommodate these motions while doing its primary work. Figure 6, describes ROM for different areas of human along with body motions. They stand as important because astronauts will be in need of hassle-free workflow with any of the devices or wearables they are going to use.

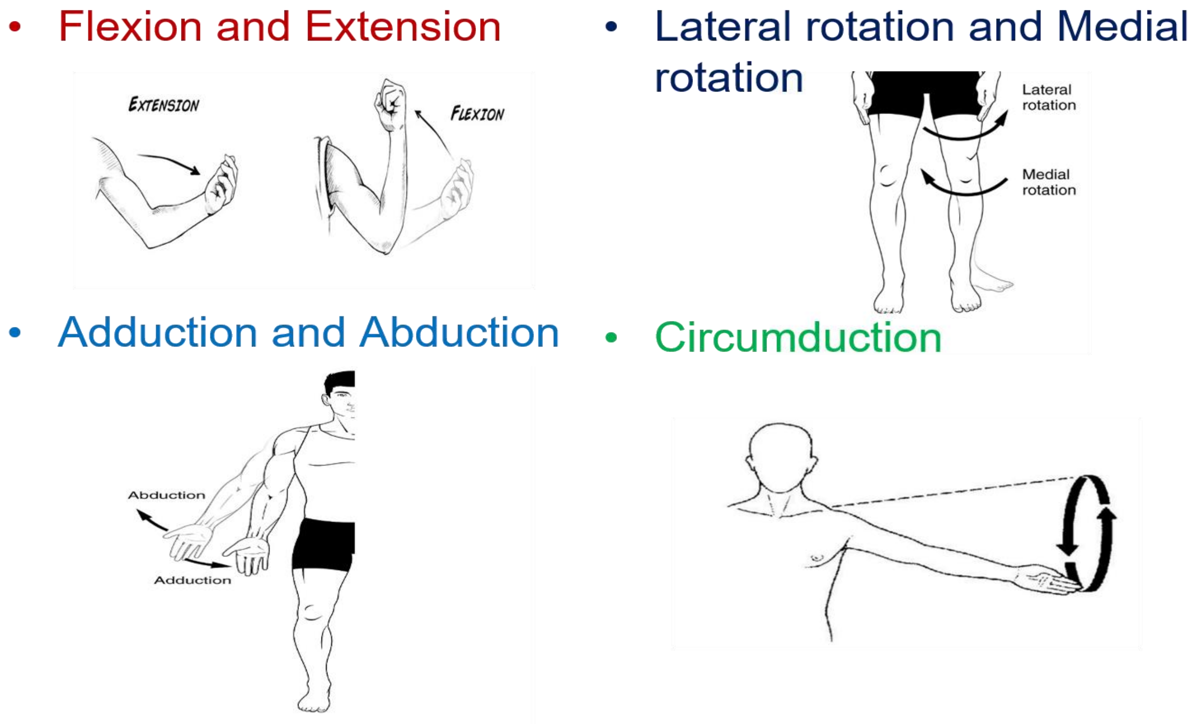


Figure 5. Body motions

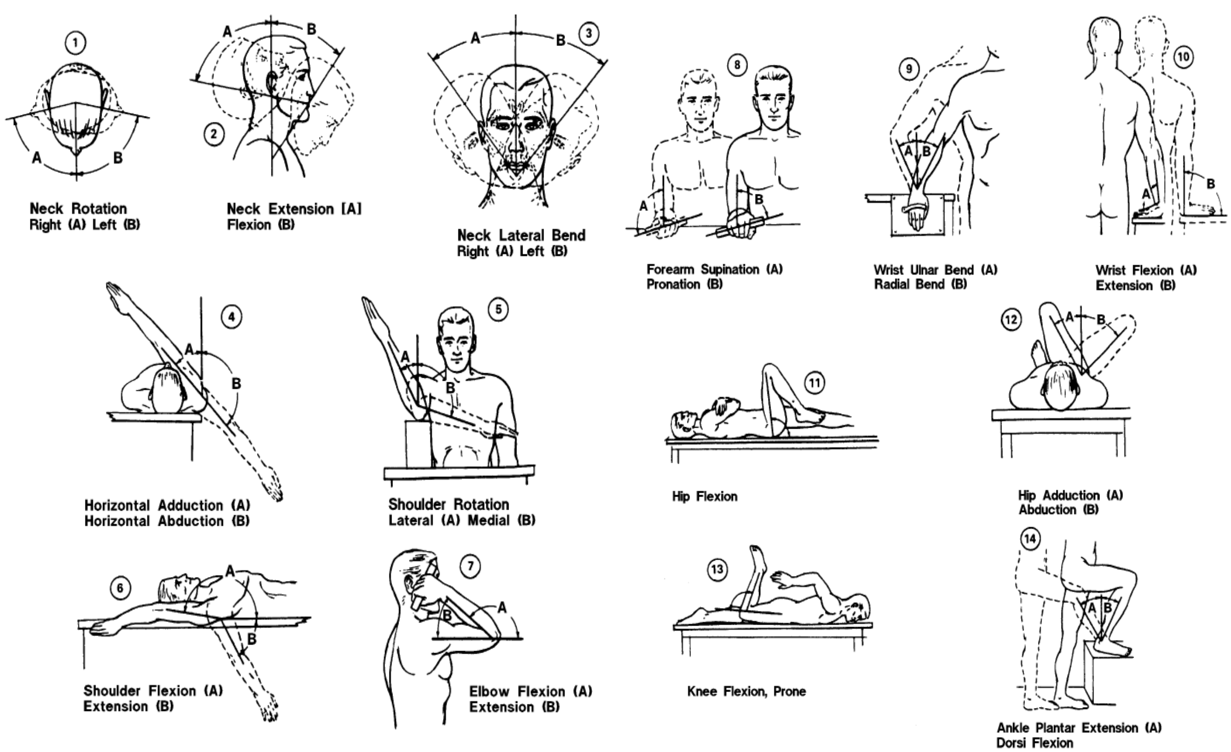
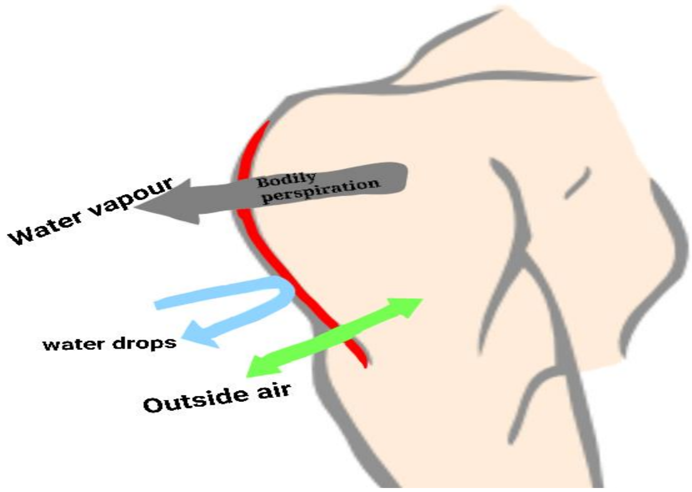


Figure 6. Range of motions for different areas of body[13]



Breathability comes next, where it refers to the ability of the skin covering the human body to respirate not the general breathing of human lungs. Our skin surface has many operations form protecting the internal organs to sending sensory information, from perspiration with surroundings to protecting our body from foreign organisms and maintaining thermal balance.

It is important to ensure all these operations are continued without any disturbance. Human body is generally naked (here it refers in terms of protection from environmental hazards) when considered to other living animals which have a thick sheet of fur around them. This led us to use clothes or fabric and many other protective equipment based on the need or working environment (they may interfere with its working but serves the basic need of protection). So, these factors need to be evaluated and deciding material is also important.

Our complex human body is designed to be always in a dynamic condition. The musculoskeletal system works to keep our dynamic body in a stable position. So, any additional load shifts the 'Centre of gravity (CG)' destabilizing the body posture. Also, we cannot add weight wherever we want due to two main reasons: 1) Shift of CG, 2) The nerves can undergo compression creating numbness at those areas. For this reason, we have decided to add weight or load the body only at well-known load bearing location **"shoulders".**

Other biological allowances: Need is the very first thing that forms as the base for all these considerations. These considerations are never ending, the more you take them into account, the more complex it becomes but which is desirable when it comes to these kinds of supportive exoskeletons. These exoskeletons are more specific to the person for whom it is being designed, so working perfectly to his or her body gives out a perfect outcome instead of a generalized design. Mostly, it depends on the user comfort and safety which accounts for major part during design.

Apart from these, this exoskeleton must ensure to have some distinctive features: In any case or situation, it should only provide additional support to the astronaut. That means it should not be a burden for him/ her. It should be easily worn and removed. It must have the capability to work alongside of human body and other systems designed for space like spacesuits, spacecraft and ISS cabin. Most importantly the power or energy requirements must be as low as possible.

WORKING PRINCIPLE

This exoskeleton is designed to create a sense of gravity for the person (astronaut) wearing it. At present it will be addressing problems related to loss of bone density, hydrostatic pressure loss, muscle atrophy and orthostatic hypotension. All these problems may seem to be different but in some sense they all are related to one another. Afterall they arose from the same human body. Figure 7, shows the relation between them. So, this exoskeleton will stand as a single point solution to the above stated problems.

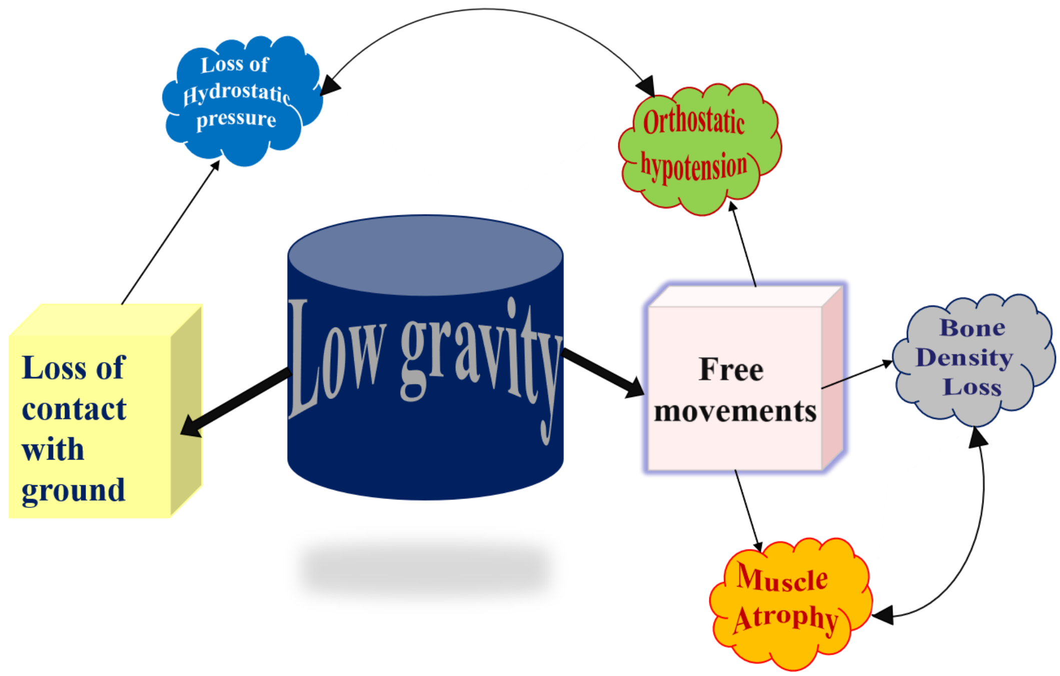


Figure 7. Relationship between problems

As astronauts start to experience weightlessness, everything around them starts to feel lighter and easy to handle. This makes it easy and require very less effort to lift any object or move their body compared to on-earth condition[14]. So, if we can restrict that free and lighter movements, he or she will be in need of additional effort to pick, place and move objects or their very limbs itself. This very idea led us to design this exoskeleton as a support for the human body in that hostile space environment.

In practical sense they are not restricted to move and work, they are placed in a situation to use additional energy to do their tasks. More precisely, they will never be put to use any additional energy than what they generally use on the earth. Also, specially designed shoes will be employed to restore the lost hydrostatic pressure and to reduce the orthostatic hypotension effect. Two designs are under considerations for this, one is using a piston & cylinder to exert pressure on the foot sole and other is to employ a 3D insole shaped bellow to exert pressure at required regions. These shoe arrangements will be working on cyclic manner to continuously pressurize and depressurize the foot sole to mimic the walking effect.

We want to use fluid power for operational energy requirements of this exoskeleton. Below in Figure 8, you can see a schematic to demonstrate the working of exoskeleton at elbow joint. Just like human body skeletal muscles, these piston & cylinder arrangements mimic its mechanism to work in tandem with each other for supporting the main idea to restrict the motion.

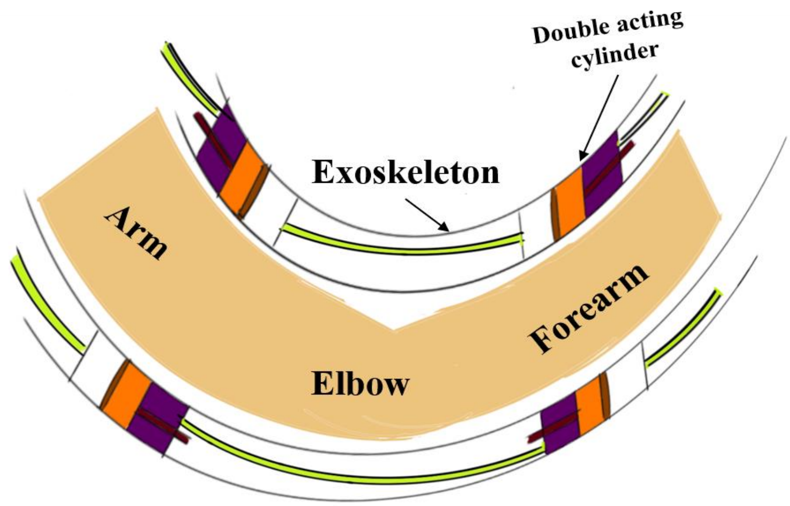


Figure 8. Schematic showing transverse section of exoskeleton at elbow

This fluid system arrangements are embedded into the exoskeleton to ensure that all of its lines won't interfere with any of the work that an astronaut is going to perform and also to make it easy for the person using it to wear and remove, just like any other dress. In figure 9, you can see different fluid system components and their regions inside the exoskeleton (on full body it will be like similar to the left side of the body as shown in the image).

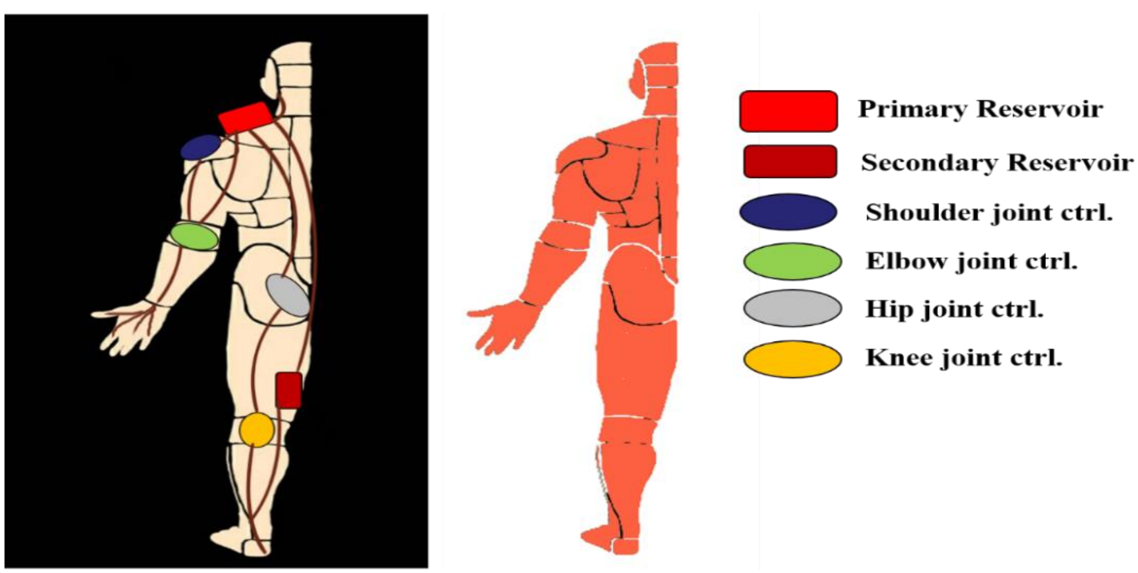


Figure 9. Schematic showing components of exoskeleton

General governing equations of fluid systems[15]:

- Flow losses in fluid pressure

$$\triangle P = \mathrm{f}\frac{\rho L}{2D}V^2$$

$$\triangle P = \mathrm{K}\frac{\rho}{2}V^2 = \mathrm{K}\frac{\rho}{2A^2}Q^2$$

$$\triangle P = \frac{\rho}{2A^2{C_d}^2}Q^2$$

- Double acting cylinder

$$F_p = P_1A_{Cap} - P_2A_{rod}$$

- Accumulator

$$C_f = \frac{\triangle V}{\triangle D}$$

DESIGNS OF EXOSKELETON

Based on the considerations and working principles, there are many things need to be designed to complete a single unit of exoskeleton. Starting with braces as shown in figure 10. These braces are designed to hold the piston and cylinders at desired location.

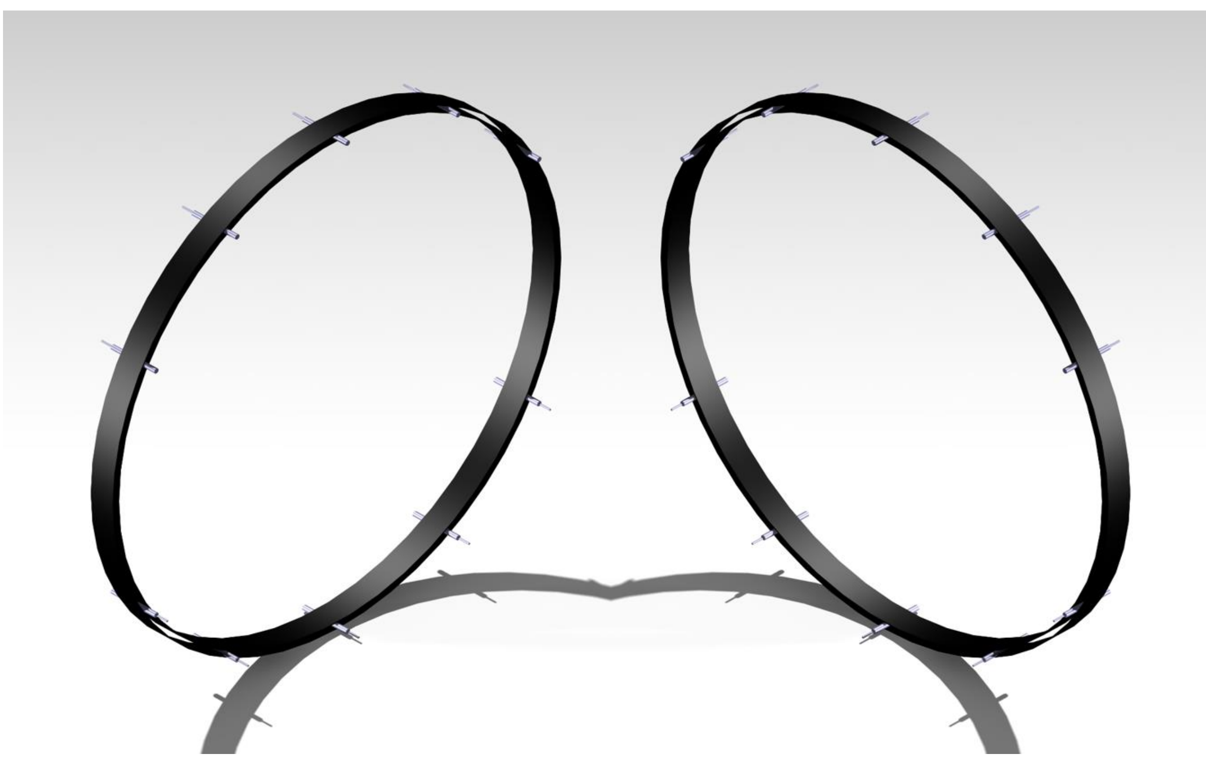


Figure 10. Braces to hold piston-cylinder assembly

They are attached to top and bottom with the exoskeleton outer part which will in contact with the human body surface or skin surface. They serve like mountings and to sustain the back pressure generated by human movement forces. The pistons & cylinders are double acting cylinders which are designed based on standard techniques but with a largely scaled down dimensions.

There are many other fluid lines which carries fluid to the required region in between those gaps present in braces. From Figure 11, you can see a number of fluid lines inside that exoskeleton from the sectioned part. The white region shows it is further sectioned to demonstrate inner features of those fluid lines. They may serve as conduits which we generally use for hydraulic and pneumatics circuits systems. These can be manufactured either by adding them between the exoskeleton or by making the exoskeleton inner surface with some gaps which can serve as the conduits.

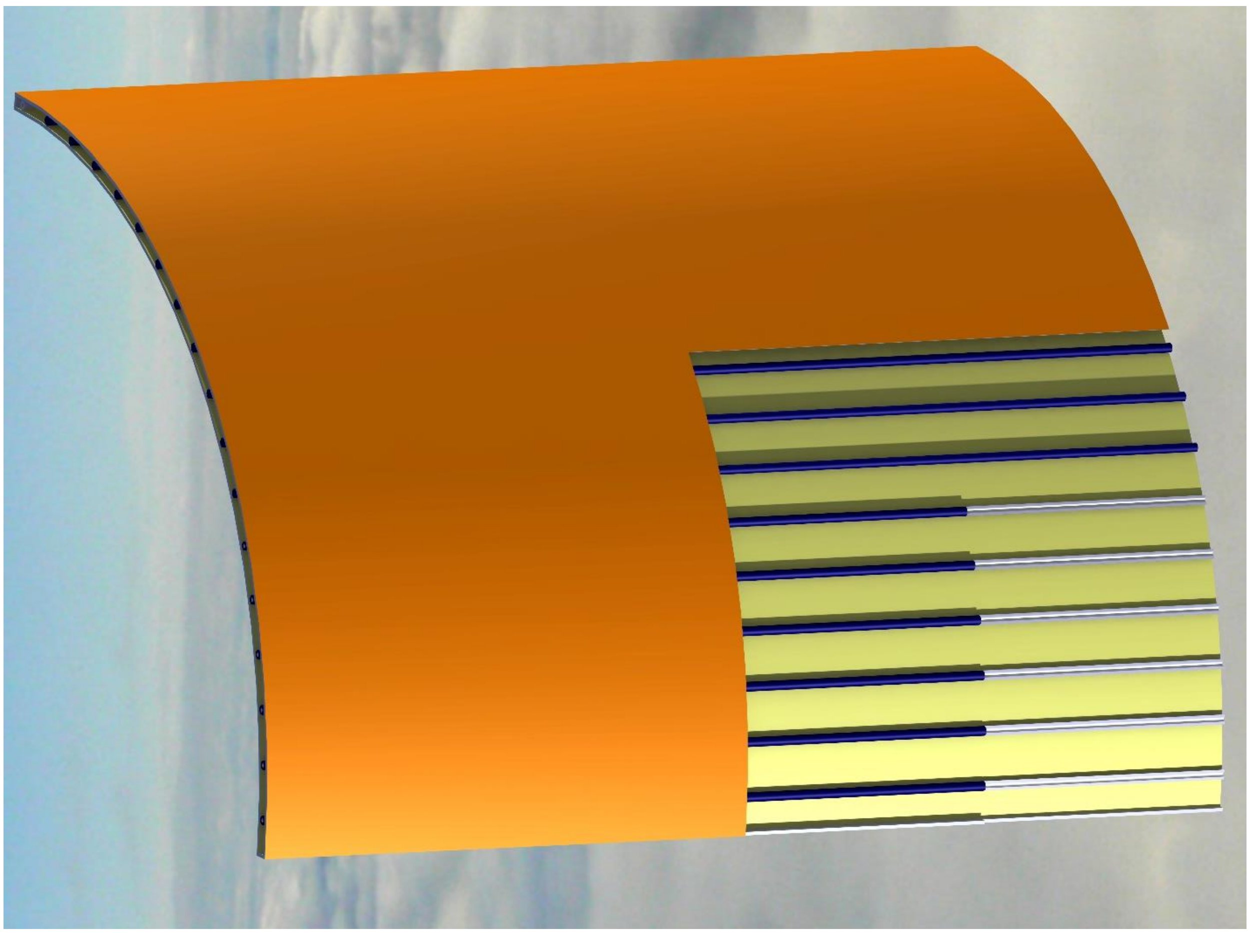


Figure 11. Sectioned view of a small part of the exoskeleton

There are many more components as you can see from figure 9, they all are embedded into the same exoskeleton and shape is altered based on our need to accommodate them inside. At joints there will be a complex set of piston & cylinder assemblies to allow hassle-free joint movements besides restricting those body movements where it is placed (in figure 9).

Coming to the bottom foot place, there is a need to exert a pressure equal to ground reaction on the foot. This can be done with the piston and cylinder arrangement shown in figure 12. The two slices show us that they are arranged in layers one above another connected by conduits. They are supplied with fluid from secondary reservoir or accumulator along with another line from the primary source. These two lines alternatively push the pistons back and forth to mimic the walking experience even in floating conditions.

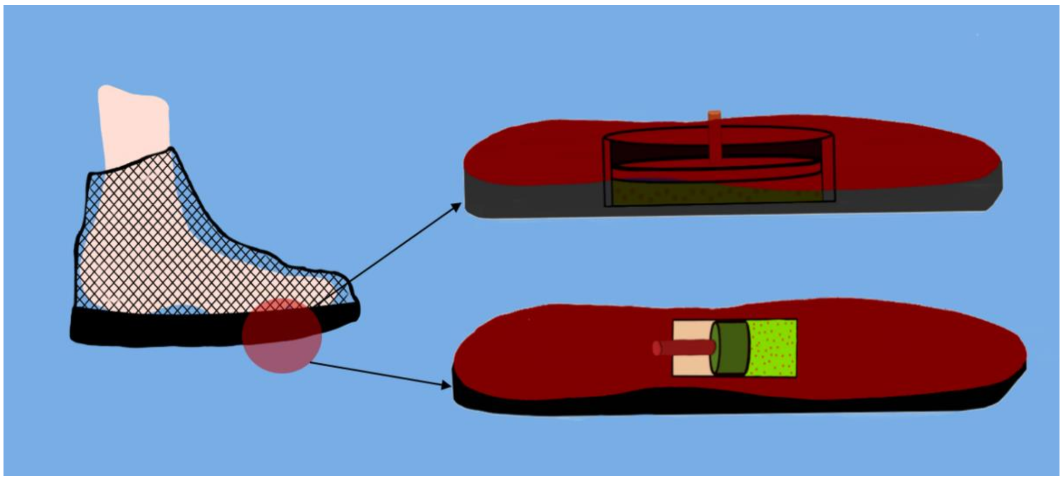


Figure 12. Sliced view schematic to show the fluid system arrangements in the shoe sole

Calculated from the MSIS dimensions average human sole surface area is 100 cm^2 and average weight is 82.2 kg. From, ground reaction force F = mg, gives hydrostatic pressure P = F/A, which is of 80638.8 Pa or 0.806388 bar. This is the pressure which is required to be exerted at sole of human foot.

There is also an alternative approach which employs a bellow type insole as shown in figure 13, which works similar to the previously discussed type of shoe arrangement, but acting with the precise values of pressures at those predetermined regions accurately. This insole will also be supplied with same amount of pressure 0.806388 bar. Combination of these two types of arrangement needs to be assessed for its complexity and ease in operation.

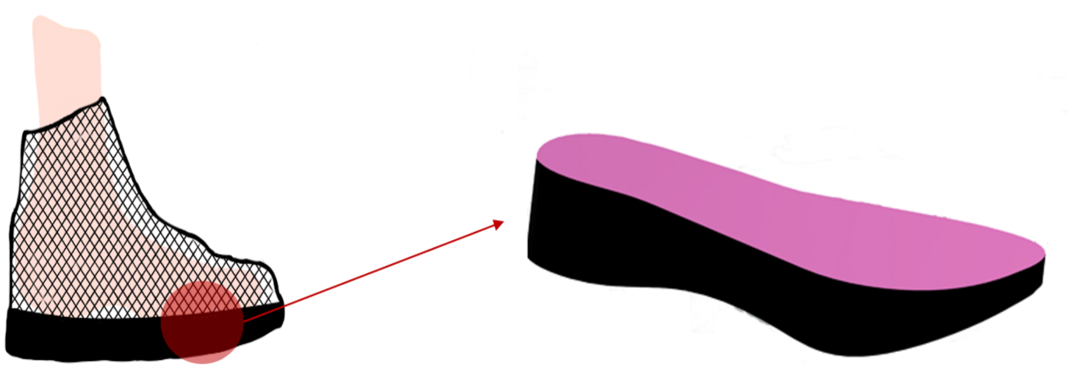


Figure 13. Bellow type insole (right side)

RESULTS AND DISCUSSIONS

The exoskeleton uses fluid power to control and operate its functions. So, it supplies pressure energy to either replace the lost values due to change in gravity or to compensate them. From table 1, you can see different values of pressure exerted by ground on human sole during a normal walking.

Table 1: Calculated values of pressure exerted by ground on foot at different places

S. no.	Name of the place	Acceleration due to gravity (m/s^2)	Avg. Mass of the human body (kg)	Ground reaction force F (N)	Surface area of foot plantar side A (m^2)	Pressure P (bar)
1.	Earth	9.81	82.2	806.382	0.01	0.806382
2.	Moon	1.62	82.2	133.164	0.01	0.133164
3.	Mars	3.71	82.2	304.962	0.01	0.304962
4.	Space or Microgravity	$1x10^{-3}$	82.2	0.0822	0.01	$8.22x10^{-5}$

There are a greater number of places on our body which are controlled by this exoskeleton. Now, consider the foot region, as previously stated in the previous section a shoe is employed which will restore or mimics the walking effect. This shoe will be working to add the pressure as listed in table 2, this process is repeated to restore the gravity feel to the person using this exoskeleton.

Table 2. Amount of pressure required to be added based on the place

S. no.	Name of the place	Acceleration due to gravity (m/s^2)	Pressure P (bar)	Ratio = g_{earth}/g_{planet}	Drop in pressure (%)	Amount of pressure to be added (bar)
1.	Earth	9.81	0.806382	1	No change	Not required
2.	Moon	1.62	0.133164	1/6.055	83.486	0.673218
3.	Mars	3.71	0.304962	1/2.644	62.181	0.501420
4.	Space or Microgravity	$1x10^{-3}$	$8.22x10^{-5}$	1/9810	99.98	0.806299

Fluid circuit schematic and its analysis

Fluid circuit design shows us all the components present inside a fluid powering system. In figure 14, you can see only half part of design as the rest is just a mirror of the other (the left and right-side controlling is almost same for the human body). The primary accumulator (two both on left and right) receives its pressurized fluid from a closed fluid reservoir found at the far right of image. This primary accumulator serves fluid to the rest of its components controlled by different valves (which govern the direction and control of fluid flow). The cylinder assemblies work according to the preset values to do the intended work. The secondary accumulator and other line from the primary accumulator at knee serve as the functional cyclic pumping devices for the foot sole. There is a pressure gauge at the fluid reservoir to indicate the pressure with which the fluid lines are currently charged with. Most of the time, this circuit is in static position (once charged it can do its works seamlessly) but if we want we can adjust them based on the need which is decided by the gravitational force (in simple terms with the change in gravity, we need to modify the pressure values). This complex looking device works with simplest elements to serve the basic need for humans to be safer at those adverse conditions.

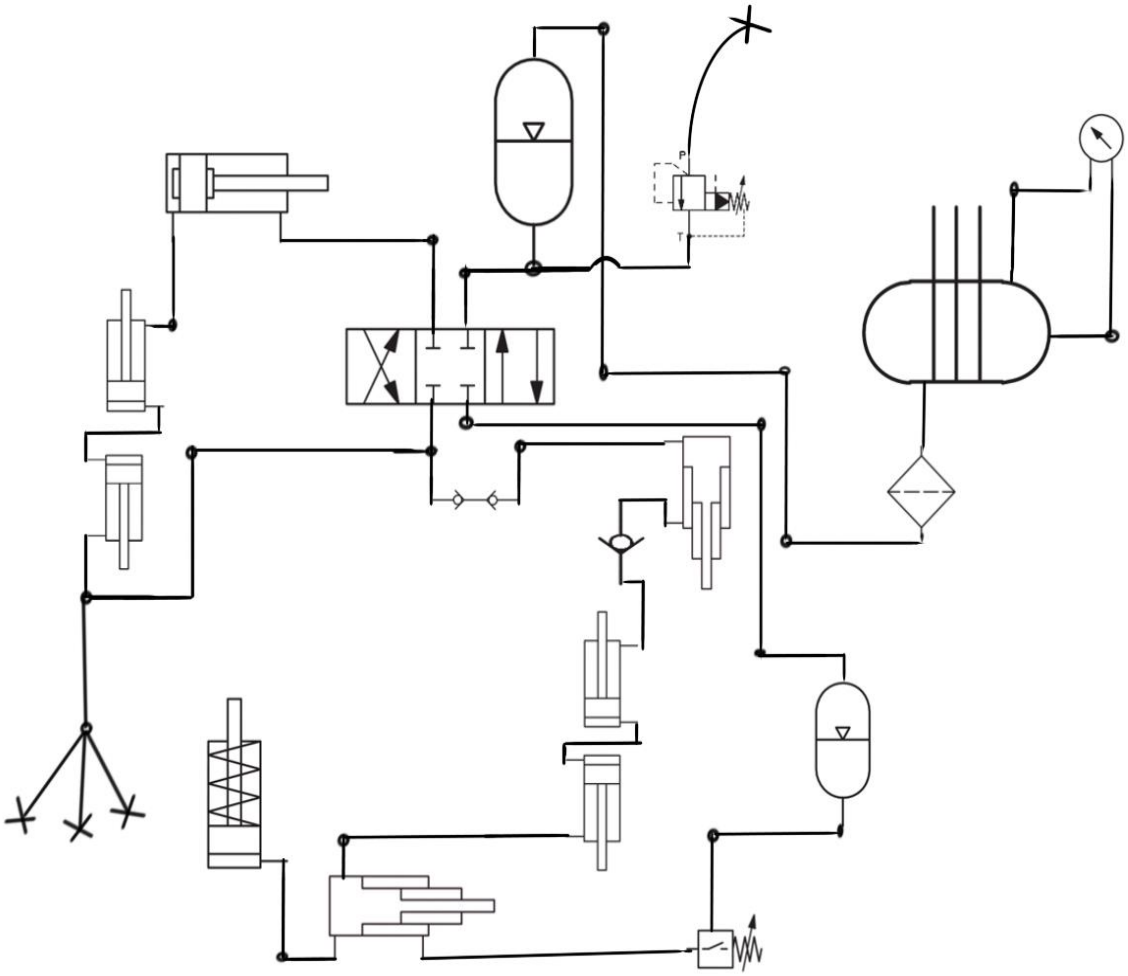


Figure 14. Schematic showing embedded fluid circuit of the exoskeleton (half side of body)

CONCLUSION

This conceptual exoskeleton design is developed from an idea to create a sense of gravity in space. Presently, this exoskeleton can address problems related with musculoskeletal and cardiovascular systems under the influence of low gravity condition during a space travel. The extra effort used by astronauts for movements during work will serve as exercise and the walking mimic created by shoe will help to restore the problems related with cardiovascular system. It can help the astronauts without interfering in their normal work and their normal body functioning. The biological considerations discussed stands unique for this exoskeleton which makes it to stand apart from other available remedies. This exoskeleton uses fluid power to manage the operational energy requirements. The exoskeleton will allow other modifications onto it, which creates space for integrating other equipments or solutions as remedy to a greater number of problems that are to be anticipated. This can be worn even inside of spacesuit which if needed. Finally, this design was prepared making it compatible with additive manufacturing for the ease of fabrication.

FUTURE WORK

Study on effectiveness of fluid power to operate this exoskeleton need to be made along with looking for alternative solutions for power requirements. During this time standard dimensions are used from man-system integration standards which may not stand in practical sense as a perfect fit. Modern human body (of astronauts) dimensioning techniques will be used to make specific designs for an individual. Integration of systems into this exoskeleton to address other problems with space travel will also be considered.

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